

RECENT GLACIAL STUDIES IN GREENLAND

ANNUAL ADDRESS BY THE PRESIDENT, T. C. CHAMBERLIN

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INTRODUCTION.

Our Society is still young and uncontrolled by precedents. The hope has been expressed that if precedents shall become established they may be expressions of freedom and individuality rather than of limitation and monotony. It has been thought that if the presidential address shall be confined to reviews and summaries and restricted to special

modes of presentation it may become more perfunctory than vital. To whatever practices your collective preferences may at length lead, I trust that between these expressed wishes and the liberties conceded to our youthfulness I shall have your sanction or, at least, your pardon if I occupy your attention with a sketch of personal studies on the glaciation of Greenland made during the past summer. I further hope that if in presentation I invoke the aid of physical illumination to supplement the dimness of my own it will not awaken your displeasure.

OBJECT OF THE STUDIES.

The purpose of these studies was to find light upon some of the obscure problems of our Pleistocene glaciation. No hope of covering the whole field was entertained. Attention was therefore concentrated upon points thought to be most promising of instruction.

The foremost questions at the outset were: How does a glacier take up its material? How does it carry it forward? How does it put it down? What functions do water and topography play in the process? A glacier's methods in respect to lateral and medial moraines, which are superficial, are simple and well known. Its methods respecting basal material, which is largely concealed, constitute the problem. The locus of study was controlled by these questions. The summits of the glaciers were but lightly reconnoitered. Their bases were as closely scrutinized as possible. The snowy heights are indeed alluring, and in the inspiring air of the northern fields one loves to mount, but light on our drift is to be sought in the dirt and drip and shadows of the bottom. The darkest spots are here the fullest of light.

In the end these leading questions were compelled to yield much of their dominance to others which grew to scarcely less vital importance.

DISTRIBUTION OF THE STUDIES.

In a geographic sense, the studies fall into three groups:

1. A cursory scrutiny of the coast between cape Desolation and Inglefield gulf, a stretch of above a thousand miles, to note the effects of former glaciation.
2. A brief inspection of three local glaciers on Disco island, near the Arctic circle, for comparison.
3. A study of the inland ice, local ice-caps, and fourteen derivative glaciers about Inglefield gulf, between latitudes 77 and 78 degrees.

COMPARISON BETWEEN GLACIATION OF MAINLAND AND GREENLAND.

In a comparison between our former glaciation and the present glaciation of Greenland two elements of difference are to be recognized. The first relates to topography, the second to latitude.

Our drift, except on the eastern border and the Cordilleran tract, is spread upon a vast plain. The ice-fields of Greenland rest mainly upon plateaus fringed by rugged mountains. To learn how a Greenlandic glacier would behave on our plains the effects of broken topography must be escaped or eliminated. Simple elevation, however, is immaterial. A plateau of smooth surface may furnish conditions identical with a plain, so far as glacier behavior is concerned. It is only necessary that the glacier deploy freely on relatively smooth ground and come to a limit by the balance of growth and wastage. It was extremely desirable, therefore, to find a portion of Greenland whose border was free from mountains. Inglefield gulf, perhaps better than any other portion of Greenland, furnishes the desired conditions. Unlike most of the coast, it is not girt by mountains. The borderland is a plateau about 2,000 feet above the level of the sea, with a summit-plain of marked uniformity. Its undulations are intermediate in strength between those of the eastern and western parts of our own glacial field. The border of the great ice-sheet may there be studied on relatively smooth ground, or it may be studied on undulatory ground, or the lobes or tongues that descend into the valleys may be chosen. In the portion in which my chief studies lay only a very small fraction of the ice was discharged into the sea. The border would in no appreciable way be changed were there no seawastage at all. Glacial tongues from one to three miles long are frequent, but it does not appear that the nature of the main ice-border would be essentially different if the valleys that caused these tongues had been absent.

The peninsulas of the region have local ice-caps from which glaciers radiate as from the great ice-cap. The habits of the small and the great ice-caps are essentially the same.

Of the 30 or 40 glacial tongues which descend toward Inglefield gulf less than one-third reach the shore, and scarcely one-half of these discharge notable icebergs. The majority terminate in valleys whose bottoms are formed of glacial debris and whose lower gradients are moderate.

RELATION OF GEOLOGIC FORMATIONS OF GREENLAND TO GLACIATION.

The geologic formations of Greenland are unfavorable in the main to glacial studies. The nearly universal presence of the ancient gneissic series makes discrimination of the origin of material unsatisfactory, when it is not impossible. Besides this, the debris is rocky and arenaceous; the clayey element is scant.

In the Disco and Inglefield gulf regions, however, the gneissic series is bordered by clastic and igneous beds that give some relief from these adverse conditions. On Disco island there is a nucleus of gneiss sur-

rounded by basalt and sandstones. About Inglefield gulf the gneissic series is covered by thick terranes of sandstone and shale which are traversed by basic dikes. The clastic series forms but a border, and is only reached by the ice near its edge. It is thus possible to tell how late the erratics from it were introduced into the ice, what courses they pursued, and what actions they suffered.

THE EFFECTS OF LATITUDE ON GLACIATION.

In so far as latitude is merely an agent of glacial temperatures, it is not necessary to consider its effects, for some equivalent cause of glacial temperatures must have been operative in Pleistocene times. It is only the distinctive results, such as may be attributed to the constancy of the sun above or below the horizon, the low angle of incidence of its rays, their impact from all points of the compass, and similar features, which need to be considered.

A partial means of determining what these are is found by comparison between the glaciers of Disco island, only a little within the Arctic circle, and those of Inglefield gulf, $8\frac{1}{2}$ degrees farther north. The Disco glaciers seem to have all the familiar characteristics of glaciers south of the Arctic circle, while the Inglefield glaciers take on habits significant of their high latitude. This will appear as we pass on.

VERTICALITY OF THE GLACIAL MARGIN.

The feature which is likely first to impress the observer, on reaching the glaciers of the north, is the verticality of their walls. Southern glaciers, as you are aware, terminate in curving slopes, and the Disco glaciers of middle Greenland have the same habit; but the margins of the Inglefield glaciers rise abruptly like an escarpment of rock, 100 or 150 feet or more. The layers of ice are cut sharp across, exposing their edges. This verticality has been observed by Greely, Heilprin and others. It is not quite universal, however, as sloping forms occur here and there. Occasionally a glacier presents both aspects. These abrupt terminal walls turn toward all points of the compass. It is perhaps too much to say that they do this indifferently, as but few glaciers facing the north were seen, but among these verticality prevailed much as elsewhere. (Figures 1 and 2, plate 3.)

The cause, with little doubt, is the low inclination of the sun's rays and their impact from all points of azimuth in succession. Rays of low slant strike the back of a glacier at a very acute angle and glance away with the greatest facility and the least effect. On the edge of the glacier, however, they strike more vertically and effectively. In addition to this, the slanting

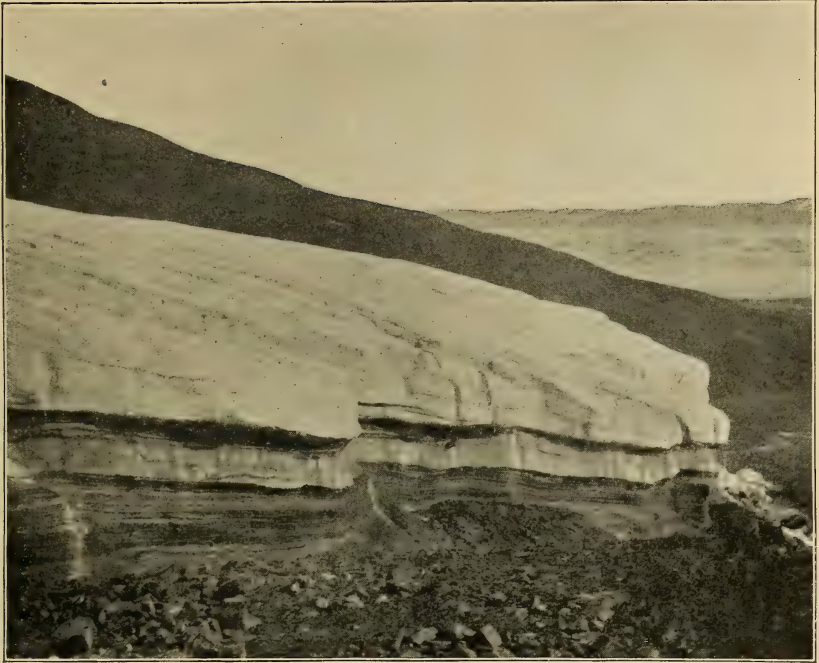


FIGURE 1.—WEST FACE OF BRYANT GLACIER.

Showing vertical wall and stratification of the ice. The amount of debris is made to appear much greater than it really is by surface wash.

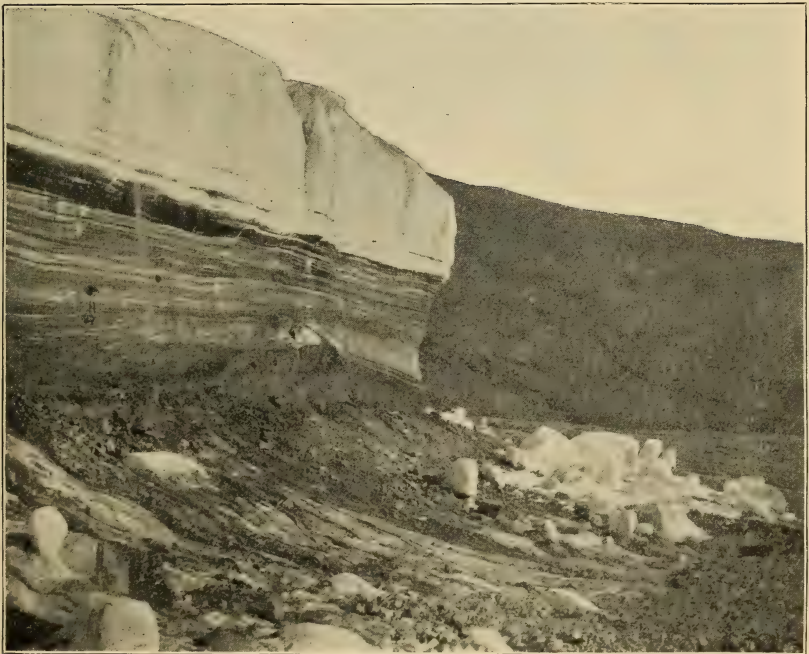
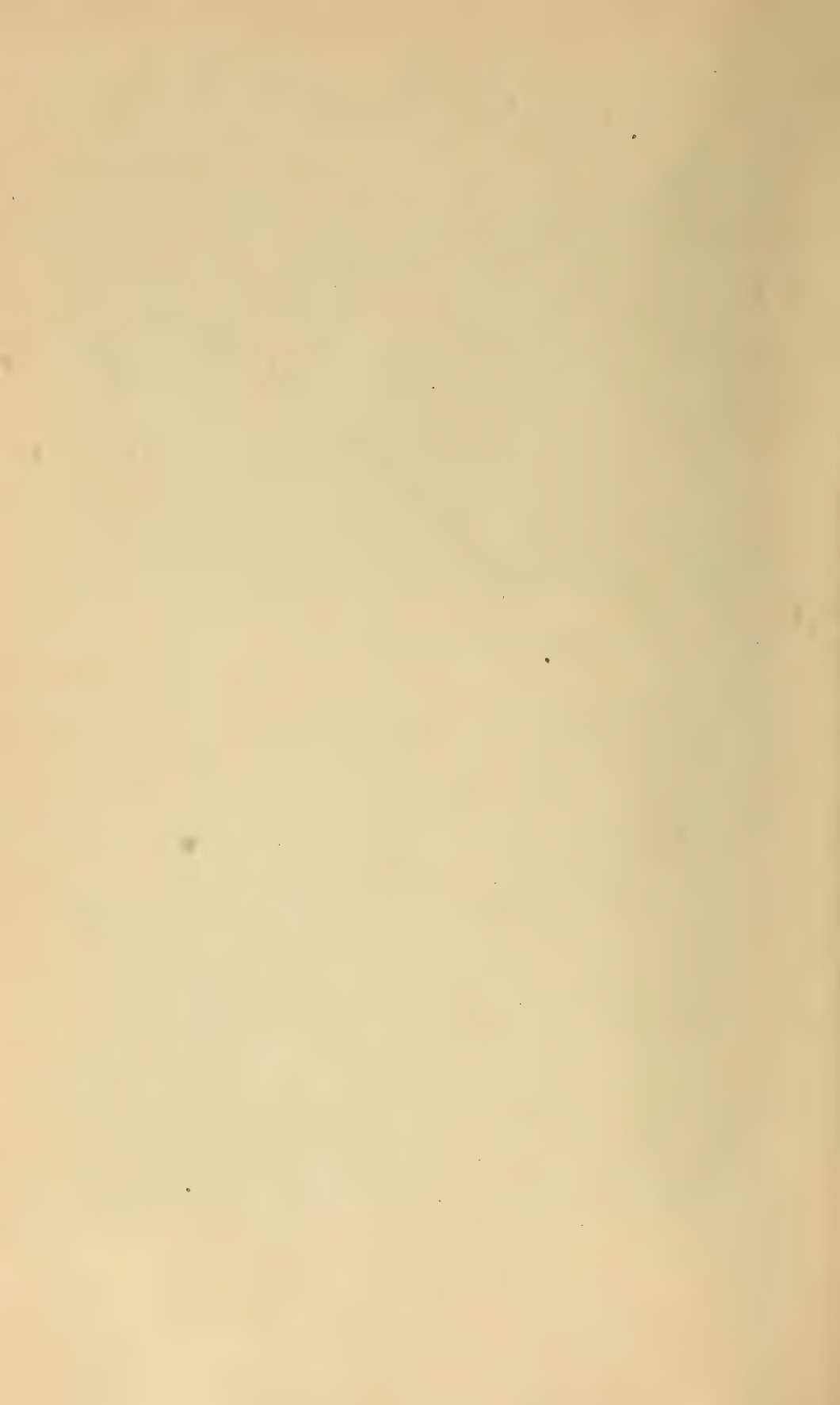


FIGURE 2.—FRONT OF BRYANT GLACIER.

Showing vertical wall and stratification of the ice.

BRYANT GLACIER.



rays, touching the surrounding earth's surface at low angles, are reflected at like low angles, and hence often impinge upon the edge of the ice. On a lake, just before sunset, you have doubtless often seen a brilliant illustration of the wide space from which rays of low slant are reflected so as to be caught by an object of slight elevation. Prominences about the glaciers catch and absorb the heat on their sides rather than their summits, and in turn radiate this heat in lines chiefly normal to their walls and favorable to reception by the edges of adjacent glaciers. It appears, therefore, that a larger proportion of the sun's rays falls on the glacier edges at the north than at the south, and it is the proportion of rays that determines the contour. It is interesting to note in this connection that nunataks are often surrounded, like an ancient castle, by a moat sunk between the foot of the eminence and the mass of the glacier, whose face is usually vertical. It is only when the movement of the ice is notably great that it presses hard against the nunataks. We must not, however, fall into the error of supposing that verticality is due simply to reflection from cliffs, because glaciers that end on broad, smooth, gravel-bottomed valleys are as vertical as any. Here it must be the direct rays and the rays reflected from the smooth surface of the valley which produce the effect.

STRATIFICATION.

General Characteristics.—Next to verticality, the most impressive feature is the pronounced stratification of the ice. The stratification of glaciers is not new, but the extent, definiteness and peculiar characteristics displayed by its phenomenal exposure in these northern regions are perhaps in some measure a revelation. The ice is almost as distinctly bedded and laminated as sedimentary rock. The vertical face usually presents two great divisions—an upper tract of thick, obscurely laminated layers of nearly white ice and a lower laminated tract discolored by debris. At the base there is usually a talus-slope, and sometimes, but only sometimes, a typical moraine. In the upper portion bluish solid layers separate the more porous ice into minor divisions, and these are grouped by consolidation into more massive layers. Sometimes the whole upper division consists of a single stratum, but more commonly it is divided into several great beds separated by quite distinct planes. (Figures 1 and 2, plate 3, and figure 3, plate 4.)

The lower discolored division also sometimes consists of one great stratum, but oftener it is divided into several great layers, as in the case of the white ice above. Very numerous partings further divide these beds into minor layers of varying thickness, grading down into delicate laminations, a dozen or a score to an inch. In addition to the bluish bands and the physical partings found above, there are here interstratified

layers of debris, which embrace not only sand and silt, but rubble and boulders. The whole may be likened to a cold sandwich—a meat and mustard of drift spread between slices of ice. Often the interspread layer consists of the merest film of silt; at other times it attains a thickness of an inch or two, and sometimes it reaches several feet; but this is rare, and it is then usually a heterogeneous mixture of debris and ice. The debris is usually arranged in very definite and limited horizons, leaving the ice on either hand as clean and pure as any other. It is very notable and significant that the ice next to the debris-layers is the firmest and most perfect ice which the glacier affords. It fractures in sharp, vitreous partings, which send forth beautiful iridescent reflections like the purest lake-ice. Seen in place, it appears black because of the dark earth above and below it, but separated from these associations it shows its true nature as clear, transparent ice. Even this ice, however, does not reach the perfection of ice-structure, but it is further advanced toward it than the great mass of the glacier.

Debris-layers and Laminæ.—The coarser debris is arranged in the same horizons with the fine debris. Often a fragment of rock will be several times as thick as the average silt-layer with which it is associated. In this case it is usually centered on the layer and projects above and below into the clean ice. In this way boulders of considerable dimensions may be associated with a mere film of fine debris. More frequently, perhaps, the larger fragments are associated with laminated bands rather than with single laminæ, and in this case it is interesting to observe that a portion of the laminæ curve downward and pass under the boulder, while another portion curve up over it. Sometimes all the laminæ part and pass around on either side; in other cases those which encounter the center of the boulder terminate there. Usually corresponding laminæ appear on the other side. The phenomenon is almost precisely like the behavior of silt-laminæ in stony sediments. (Figure 4, plate 4, and figure 13, plate 9.)

The debris-layers are not at all uniform in their distribution. Often they have much regularity and persistence; often they thin out and disappear within a short distance; more often still they persist for a few rods and are replaced by adjoining layers which come in as these thin out. Thus a belt of layers has much persistence, while the constituent layers are freely entering and vanishing. Lenses of debris occasionally appear among the layers, and a doubling back of the layers upon themselves, giving a lenticular section, is not uncommon.

The laminæ are sometimes very symmetric, straight and parallel, but often they are wavy and undulatory. In many instances they are greatly curved and sometimes contorted in an intricate fashion. As Dr. E. von

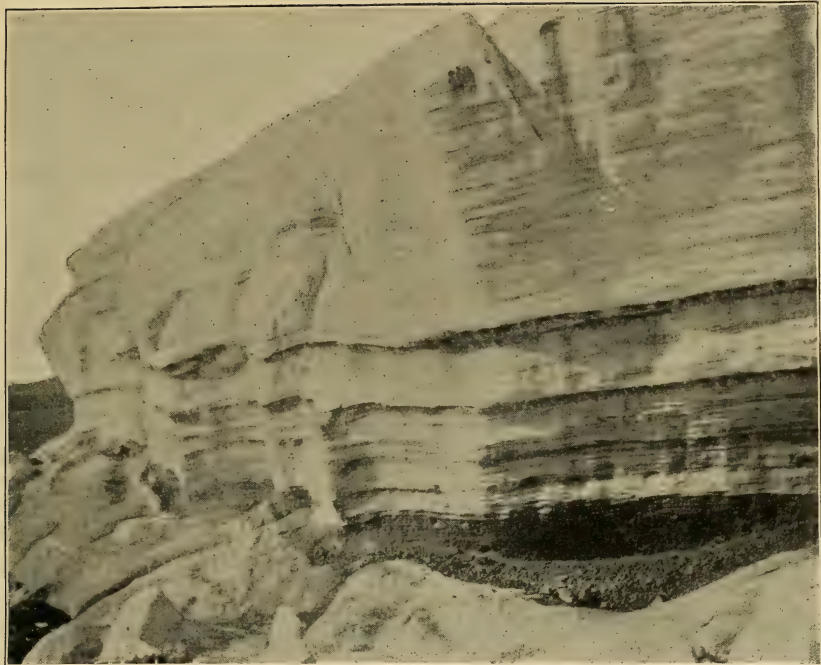


FIGURE 3.—EAST FACE OF BRYANT GLACIER.
Showing vertical wall and stratification of the ice.



FIGURE 4.—LOWER PART OF VERTICAL WALL OF GABLE GLACIER.
Showing inset debris, lamination, faulting and drag.

BRYANT AND GABLE GLACIERS.

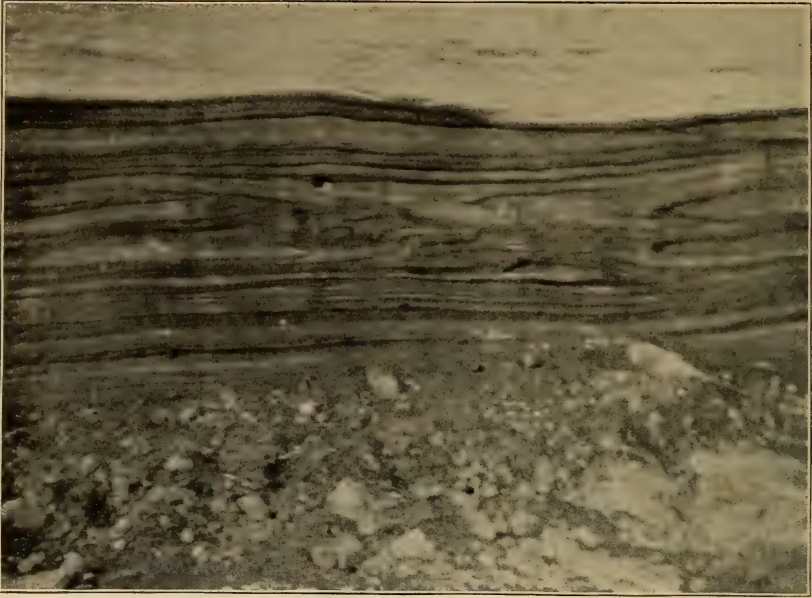


FIGURE 5.—LOWER PART OF PORTION OF EAST WALL OF BOWDOIN GLACIER.
Showing lamination, faulting, drag and overjutting of layers.

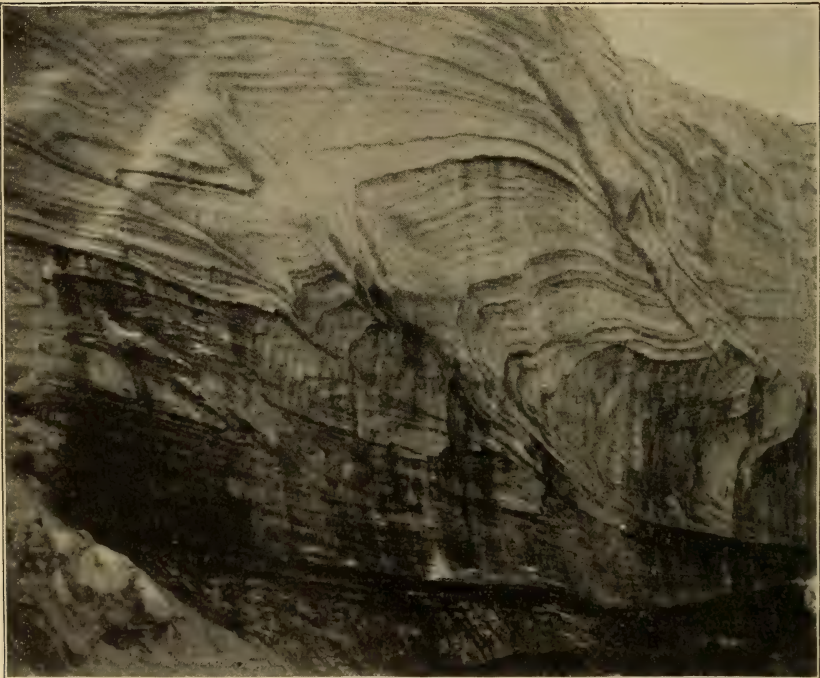


FIGURE 6.—A PORTION OF EAST FACE OF BOWDOIN GLACIER.
Showing an oblique upward thrust and distortion of laminae.

BOWDOIN GLACIER.

Drygalski has remarked, they closely simulate the foliation and contortion of gneiss. Indeed, the whole structure is perhaps as well described by the term "foliation" as by any other in common use. (Figure 6, plate 5.)

The debris belts are essentially parallel to the base of the glacier. They are chiefly confined to the lower 50 or 75 feet; sometimes they prevail up to 100 feet and rarely beyond. I think 150 feet might be named as a rather extreme limit. They are more abundant at the sides of the lobes than in the center, a fact that is significant in indicating the introduction of a notable part of the debris after the lobes were formed. In consonance with this, the debris appears to be most abundant in the glacier-lobes which descend as cataracts or crowd between closely hugging cliffs. If, standing in front of a glacial lobe, the dirt bands are traced, many will be found disappearing toward the axis of the lobe. If, standing on the side, they are traced upward, many will be found disappearing at the cataracts or at the embossments of the bottom or at spurs on the sides.

In meeting obstacles in front, the basal beds have the habit of curving upward, carrying their debris with them. Terminal moraines are sometimes thus made, resting on the edges of the ice-layers which formed them.

In front of obstacles the layers are sometimes simply curved upward and pass over the prominence; but if the frontal slope be steep, much crumpling of the laminae may take place. (Figure 13, plate 9.)

Faulting.—Not only are the foliations twisted in gneissic fashion, but they are fractured and faulted, and along the fault-line the laminae are effected by drag precisely analogous to that found in faulted rocks. (Figure 5, plate 5.)

Origin of the Stratification.—Two classes of phenomena are obviously embraced in the stratification, the one relating to the bedding of the ice irrespective of the debris-layers, the other relating to the introduction of them. The first is a general phenomenon; the second is superinduced.

Beyond serious question, the general stratification had its initial stages in the original snowfalls. Whenever encrustment intervened between one fall and another, a layer of more or less definiteness resulted. Whenever a succession of falls was followed by a period of encrustment, a more complex and massive layer was formed. The seasons doubtless developed annual subdivisions, and possibly, at intervals of a few years, unusual summer effects bound the deposits of a succession of years into a great stratum. It is the testimony of Lieutenant Peary and his associates that the surface of the ice-cap, under the action of the great wind-storms, becomes marble-like in solidity and texture, as well as in color. At the same time the erosion of the wind develops sastrugi, which further

differentiates the accumulating snow. In view of these varied agencies of stratification, it is doubtful if we can look with any confidence for criteria by which the annual snowfall can be safely distinguished from that of other periods.

The original stratification could not have been very pronounced. Perhaps it was intensified somewhat during subsequent consolidation, but some new agency was necessary to produce the more definite partings and to introduce the layers of debris. This agency appears to have been a shearing movement between the layers. On almost every one of the vertical faces certain layers jut out sharply over those beneath. Sometimes there are six, eight or ten of these projections, one above another, ranging from a few inches to one or two feet. In rare cases the projection reaches eight, ten or fifteen feet. At first sight this seemed clear proof of a shearing motion,* but upon more critical study it was ascertained that there was usually earthy matter in the upper part of the under layer which caught the sunlight and was melted back faster than the pure ice above, and suspicion arose that the whole phenomenon might be attributed to differential melting under the influence of the very oblique rays of the sun. In following a given projection laterally, it often terminated where the earthy impregnation ceased. Of course, the shearing and the impregnation might have been companion phenomena due to a common cause, but the observation gave ground for doubt as to the trustworthiness of this class of evidence. More direct proof was sought in the grooves or flutings, which it was supposed erratics, lying in the junction or inequalities of the layers, might produce. The search met with apparent success. Fluted surfaces were found. The under surfaces of many of the overprojecting beds were fluted, and, at first sight, this seemed to give abundant and incontestable evidence of shearing, but here again more careful study made it appear quite certain that much of this fluting was due to the water which trickled down the face of the overlying layer. Instead of dripping freely away when it reached the edge of the ice-cornice, it followed the under surface backward and fluted it. In most cases I could not tell whether the fluting had been initiated by shearing and merely developed by the water or not. In searching for fluting not attributable to water-action I found instances where the junction-plane marked by debris was itself fluted, the earthy material passing backward between the layers in a corrugated form.

Another class of evidence was found in the fallen blocks of stratified ice which had entered upon the initial stages of disintegration sufficiently

*The term "shearing" is used in this discussion in its common mechanical sense, signifying differential movement along a plane, and not in the ultra-physical sense, which embraces all movements of particles upon each other, even those of liquids and gases.



FIGURE 7.—PORTION OF SOUTHEAST FACE OF TUKTOO GLACIER.

Showing projection of the upper layers, apparently due to overthrust



FIGURE 8.—PORTION OF SOUTHEAST FACE OF TUKTOO GLACIER.

Showing projection of the upper layers and the fluting of their under surfaces.

TUKTOO GLACIER.



FIGURE 9.—PORTION OF NORTH SIDE OF GABLE GLACIER.

View is near junction with main ice-cap and shows method of intrust of debris-layers.



FIGURE 10.—PORTION OF NORTH SIDE OF GABLE GLACIER.

The view is taken below the one above, and shows an overthrust with debris along the plane of contact; ice much veined.

GABLE GLACIER,

to disclose the intimate nature of their mass. Definite planes of parting were developed between some of the layers. This was often true even when the layers were not separated by any earthy filament, the ice on both sides being white and pure. The plane of parting between the layers was often slightly gaping at the surface; sometimes the two layers seemed to be peeling apart. I found it easy by a moderate stroke of the spike of my alpenstock to split blocks along these partings. The separated blocks presented smooth surfaces, which seemed to leave no question of their analogy to slickensides. The layers on either side were made up of coarse granules of ice, intimately interlocked, so that an attempt to cleave the mass at other points resulted in a fracture of the most ragged and irregular sort.

But the best evidence of the verity of shearing between the ice-plates lies in the intrusion of the earthy material itself. I was fortunate enough, unless I misinterpret, to observe the actual process of intrusion. The best illustration was found on the north side of a short lobe of the great ice-cap designated the Gable glacier. Just back of the point of observation there was a large embossment of rock, which expressed itself at the surface of the ice by a beautiful halfdome, like the Halfdome of the Yosemite. The other half of the dome was cut away, revealing the operations at the base within. Here it was observed that trains of debris, apparently rubbed from the surface of the embossment, were being carried out almost horizontally into the ice in its lee. Some of these were short, while others extended several rods into the ice. They were somewhat inclined downward, but the slope of the glacier being greater, they passed out into the body instead of following the base of the ice. At one point the overthrust reached such a degree as to carry the earthy layers obliquely almost across the thickness of the glacier, producing a pronounced unconformity. The illustrations will show these phenomena with an accuracy and vividness quite beyond the power of a verbal description. (Figures 9 and 10, plate 7.)

On the East Branch glacier a similar phenomenon was observed below a cataract of the ordinary type. Here tongues of debris, having their origin in the boulder-clay below the glacier, were seen to reach out into the basal portion of the ice as though they were being introduced into it by the differential movement of the layers upon each other. The mode of operation seems to be this: When the ice is forced over a prominence it settles down a little in its lee, and is then protected somewhat from the thrust of the ice behind; the next ice that passes over, being prevented by the former portion from settling down at once, is thrust forward over it. To some extent this is accomplished by the bending and doubling of the layers and to some extent by distinct shearing. At length, however,

the first layer is compelled by the general friction to move somewhat forward, and in time to join the common moving mass, carrying the overthrust layer of debris between it and the ice-layer above. The way is then opened for a repetition of the process. This picture of the behavior of the ice is quite radically different from that entertained by the viscous hypothesis, in which the ice is supposed to flow down the lee side of a prominence, as if it were liquid. The motive power here seems not so much gravitation pulling a fluent body forward as the thrust of a rigid body by a force in the rear.

Behavior of the Ice in passing over low Prominences.—Several excellent opportunities for observing the behavior of ice in passing over low embossments were offered. From the front of the embossment there originated laminae which extended backward with a graceful, arching curve, much like the profile of a drumlin. A portion of the ice remained between these curving laminations and the upper and rear portion of the embossment. After reaching a point in the rear of the embossment, the laminae curved downward with increasing rapidity until well in the lee, when they turned about at a more or less sharp curve, or even angle, and ran backward to some point not far in the rear of the embossment, where they ended. The higher laminae made the longest curves and had the sharpest angles in the lee of the embossment. It appears obvious that the ice in the lee of the embossment moved more slowly than that above; hence the doubling of the laminae upon themselves. It appeared upon close inspection that some of the inthrust layers described above consist in reality of very sharply reduplicated laminae. It seems, therefore, that this phenomenon grades insensibly into the preceding. A study of laminae not associated with embossments showed many signs of doubling upon themselves in a similar way. It appears, then, that there is a gradation from laminae that simply suffered doubling up to layers that obviously sheared upon each other and produced manifest unconformity by pronounced overthrust. (Figures 11 and 12, plate 8; also figure 9, plate 7.)

Development of blue Bands.—Some of the laminae observed to originate on the brow of embossments of rock were simply blue bands. They were even seen on boulders underlying the ice. So far as observed, the blue bands started at some little projection or rugosity in the brow of the embossment. From this point they extended rearward, usually curving a little upward and free from the embossment, following a drumloidal curve until they had passed its lee, when they turned downward and sometimes returned as described above. Now, it is interesting to note that within the curved loop in the lee of the embossment I observed in one instance several nearly vertical blue bands, standing parallel to each

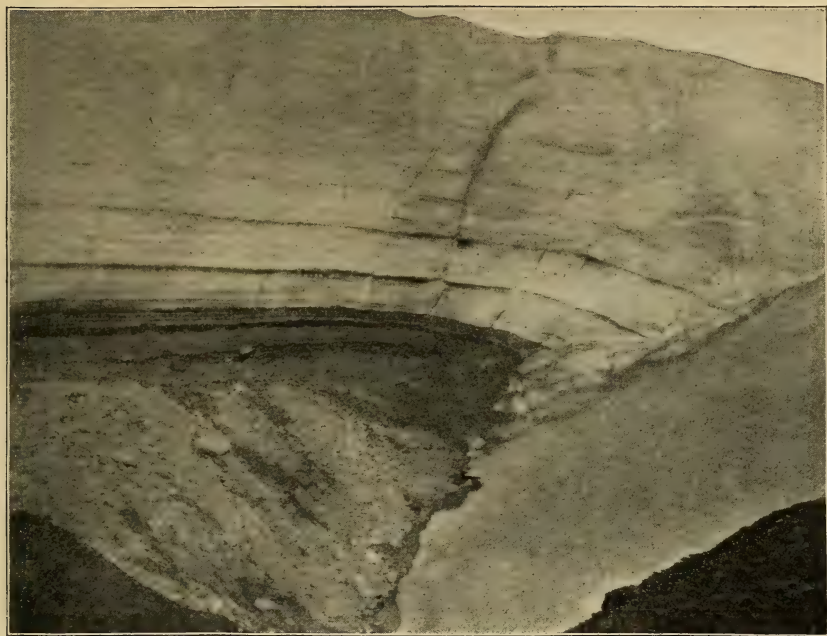


FIGURE 11.—PORTION OF EAST SIDE OF FAN GLACIER.

Showing behavior of the ice in passing over a low embossment of rock and drift. This figure shows only the upper portion, the next only the lower portion; the central part, of about equal length, not shown. Motion from right to left.



FIGURE 12.—LOWER PORTION OF ABOVE VIEW OF FAN GLACIER.

Showing the curving down and bending back of the laminae in the lee of the embossment. The prominent dark line in the center turns back with a sharp curve a short distance beyond the limits of the view, and is apparently continuous with one of the bands shown very obscurely in the lower left-hand portion of the picture.

FAN GLACIER.

other and stretching part way across the space embraced in the loop. Here it would seem that the blue bands are produced by the exceptional pressure of the ice in moving over rugosities on the brow of the embossment, and that their position in the ice is parallel to the ice-movement, while at the same time blue bands may also be developed nearly at right angles, after the analogy of slaty cleavage.

It has already been remarked that the most solid ice was usually observed in immediate association with the laminae of earthy matter. The inference is, therefore, that the agencies which introduced the earthy material by the same act developed solid ice. Independently of either of these forms, it appeared to be beyond serious question that solidified layers of ice were developed out of the crusts of the original snow, and hence that a variety of the bands is a direct derivative of the original stratification. In so far as the general shearing of the strata upon each other takes place independently of the special process by which earth was introduced, to that extent, I judge, the faces which moved over each other developed greater solidity than the adjacent parts and approached the more perfect ice of the blue bands. I am not sure that these observations traverse in any serious way the current doctrine, which we owe to Tyndall, that the blue bands are chiefly the product of pressure in constricted portions of the glaciers or in the descent of cataracts, but they do suggest that this doctrine needs limitation and qualification.

Summary.—In a word of summary, therefore, it would appear that stratification originated in the inequalities of deposition, emphasized by intercurrent winds, rains and surface meltings; that the incipient stratification may have been intensified by the ordinary processes of consolidation; that shearing of the strata upon each other still further emphasized the stratification and developed new horizons under favorable conditions; that basal inequalities introduced new planes of stratification, accompanied by earthy debris, and that this process extended itself so far as even to form very minute laminae.

DISCUSSION OF CAUSES OF MOVEMENTS OF GLACIERS.

Individuality of Ice-layers.—There is involved in the foregoing conceptions the idea of an ice-layer acting as a unit of movement, or at least individuality of movement in the layer is recognized, an idea that, if correctly entertained, is one of some importance, I think, in the physics of glaciers. This view involves the idea of rigidity rather than viscosity. It will not have escaped attention that the explanation heretofore given of the introduction of earthy material into the ice-layers involves the idea of thrust rather than pull. The picture is not that of gravitation

pulling a thick, stiff liquid down the lee side of an embossment, but of a rigid body thrusting itself over its crest.

It is not easy to escape the influence of these observations if we push inquiry back to the cause of movement. Competency to thrust and measurable ability to individualize itself in layers seem to be requisites. A general force might perhaps so individualize itself, but the phenomena naturally lead us to seek an agency acting within the layers. The limits of this address will not permit me to enter far upon the mooted question of the cause of glacial motion, but the hypothesis that has come to be dominant as the result of the summer's observations may be briefly indicated.

Granulation.—Back of the stratification of ice lies the phenomenon of granulation. A glacier starts with snow-crystals or snow-pellets; thence there is a growth into shot-like granules, and thence into larger and larger accretions. Drygalski places the limit at the size of walnuts. So far as macroscopic study goes, this progressive growth of granules constitutes the most essential change through which the ice passes. This invites the inquiry whether the essence of glacial movement does not lie in the changes which the granules undergo. If for a moment we entertain the quite erroneous supposition that all the granules of a given horizon grew from the smallest to the largest dimensions, it would appear that the expansion of the layer and the movement at its free end would be very great. Every doubling of the diameters of the granules would push the foot of the layer forward a distance equal to the whole length of the glacier. The western slope of the Greenlandic ice-field in the northern tract is probably 500 miles. Three or four doublings of the constituent granules would push its foot, if unmelted, over into Alaska; but it is obvious that each original grain does not develop into a larger one—some are sacrificed for the growth of others. The hypothetical case is introduced to emphasize this and to illustrate the possibilities of motion involved in changes of the constituent granules. It would be exceedingly helpful if we knew the laws which determine the destruction of some granules and the growth of others. The process of progressive granulation obviously involves the melting of some particles and the freezing of the water in new relations. The vital question is: At what points do melting and freezing respectively take place and what are the results? We owe to James Thompson the law that pressure lowers the melting point of ice. Whatever incompetency this may have as a sole agency, it may be an extremely efficient factor in determining the precise points at which melting will take place when both heat-energy and differential pressure are present. I suppose the converse of Thompson's law also holds true. We owe to Faraday and Tyndall the observation that ice

melted under pressure promptly freezes again when free from pressure. We owe to the same investigators the law that freezing is facilitated by the presence of frozen surfaces in close juxtaposition. We owe to Tyndall the doctrine that isolated particles or points of ice melt more freely than others from lack of support on either hand. Here, therefore, is a group of agencies which favor melting under certain conditions and freezing under other conditions. Now, all of these conditions affect the individual granule as it occurs in the mass of a glacier. It has its points of contact and pressure, its points of free surface, and its capillary interspaces. It is subject to pressures, torsions and tensions, according to the stresses imposed upon it by neighboring granules. It is always under the influence of gravity acting directly upon it, and also indirectly through surrounding granules. The combined effect is a resultant pressure urging motion down the slope, but with every yielding of the granules, by melting or otherwise, there is a new adjustment of pressures, torsions and tensions, and hence new susceptibilities to melting and freezing. Now these being the conditions of the granules, it seems only necessary that there pass over them an agency capable of acting upon the different susceptibilities of their different parts to produce loss here and gain there, and hence to determine the growth of some parts of each granule and the decadence of other parts. In other words, a granule may continually change its form by partial melting and freezing, by loss in one part and gain in another, and through this may either move itself or permit motion in its neighboring granules, or both.

Now, every warm day sends down into the glacier a wave of heat-energy. This enters the upper surface as sensible temperature, but for the most part it is soon changed to potential heat-energy in the form of melted ice. We should not fail to see that the sheet of melted ice that creeps down between the granules of the glacier as the result of a day's sun-action is as truly a wave of heat-energy as if it remained in the form of sensible temperature. With what freedom the day's heat is conveyed below by the melted product is not accurately known, but there is good evidence that it is large. Upon the Igloodahomyne glacier we observed at midday that the dust-wells were covered with thin films of ice, from which the water below had shrunk away to an average distance of perhaps two inches. The suggestion was that this was the amount of absorption of water which had taken place since the freezing of the film during the preceding night, or, in other words, the absorption of perhaps twelve hours. Circumstances did not permit the careful watching of an individual well, and this inference was not verified, but it is certain that wells of the largest sizes become entirely emptied of their water within a few days after cold weather cuts off their supply. The moisture which,

according to the testimony of all observers, pervades the interior and basal portions of glaciers, has, with little doubt, mainly descended from above.

We seem, therefore, altogether safe in repeating that every warm day sends down into the glacier a wave of heat-energy, sensible or potential, and that every night sends after it a wave of reverse nature. These waves follow each other indefinitely, until by intercurrent agencies they become vanishing quantities. Each season sends through the mass a greater and more complex wave. The problem, therefore, in simplified form, postulates a mass of ice-granules predisposed to melt at certain points and to freeze or to promote freezing at others, acted upon by the ever present but differential force of gravity and swept by successive waves of heat-energy competent to cause melting where predisposition to melting exists and to cause growth by freezing where predisposition to freezing exists. Out of this it would seem that localized freezings and thawings, growths and decadences, innumerable and constantly changing, must result, and with them motion of the granules themselves and of the common mass. This statement lacks very much in completeness and qualification, and I can only ask you to accept it as indicating the line of thought to which the observations of the summer have led.

If the truth lies along this line, it is obvious that these evolutions would proceed with different rapidity in different portions, and that they might affect an individual layer in a degree different from its neighbor layer, or they might affect the common mass to a nearly equal degree, and that therefore differential movements, alike with common movements, would be possible under suitable conditions, and that gravity would control the whole mass much as if it were a liquid.

Viscosity.*—My observations seem to be adverse to anything which can be properly termed viscous fluency. On two or three of the glaciers it was observed that the surface rises in the direction of the movement of the ice, so that the surface streams flow backward. Possibly this may be explained on the basis of a viscous flowage of the mass, but it seems much more consonant with the view that the ice-mass was pushed forward by its own internal molecular changes, and that it rode up over the inequalities of its bottom as any flexible but relatively rigid sheet would do.

*The term "viscosity" unfortunately has two senses which are nearly contradictory. Both are derived from the original use of "viscous" to signify a sticky, gelatinous, tenacious, semifluid substance, such as the exudation or extract from the sap of the genus *viscum*. In one case attention is fastened on the pliancy or semifluidity; in the other, on the adhesiveness or tenacity. In the first case viscosity becomes opposed to rigidity and implies an element of fluidity; in the other it only needs to be indefinitely increased to become identical with rigidity, infinite viscosity being perfect rigidity. The term is commonly used in glacial discussions to signify a degree of fluidity, while in physical investigations it more commonly means a degree of tenacity.

The extreme fragility of the ice is difficult to harmonize with the idea of viscosity. It was noticeable that whenever the ice passed over an undulation of even moderate dimensions it was abundantly crevassed. The movement of the ice in most such instances was obviously exceedingly slow, so that the tension brought to bear upon the surface by the small curve was relatively slight and came into action with exceeding slowness. If the property of stretching were possessed in any but the very slightest degree it would seem that crevassing would be avoided. This objection, which was long since forcefully urged by Tyndall, becomes intensified when applied to the broad, slowly moving ice-sheets of the far north.

Lieutenant Peary called my attention to a glacier on the south side of Inglefield gulf which breaks entirely in two in passing a steep descent, and reunites below and moves on. Similar phenomena are well known, but they become more emphatic in this northern region.

I saw no indication that bowlders descend through the ice as heavy substances descend through viscous bodies. As already remarked, the laminae on approaching a bowlder usually divide and a part curves under and a part curves over it. Nowhere was seen any indication that the bowlders had carried the laminae down, as the superior specific gravity of the bowlder might be expected to do in a viscous body.

Everywhere the aspect of the ice was that of rigidity rather than viscous fluency. The rigidity, to be sure, did not prevent contortions and foldings of the laminations, such as take place in crystalline rocks, but faulting and vein structures also occur, and there seems no more occasion to assume viscosity in the one case than in the other. Even if a certain measure of viscosity be admitted, it does not follow that viscosity was an essential agency of motion.

There is a theoretic objection to the assumption of viscous flowage in the very fact of crystallization itself. The property of viscous flowage rests upon the relative indifference of a particle as to its special point of adhesion to its neighbor particle. The property of crystallization rests upon the strongest preferences respecting such relationship. Particles of water in their fluent condition lie against and cohere to each other indifferently. When they take on a crystalline form they arrange themselves in specific relationships by the exercise of a force of the highest order. In the presence of this very forceful disposition of the particles to retain fixed relationships to each other, it would seem little less than a contradiction of terms to attribute to them viscous flowage. The crystalline body may readily be made to change its form by the removal of particles from one portion by melting and their attachment at other

points by congelation, but not, I think, by the flowing of crystallized particles over each other while in their crystalline condition.

RELATION OF THE GLACIERS TO THEIR DEBRIS.

The northern glaciers afford little that is new respecting lateral and medial moraines, and they may be neglected. It has already been seen that much basal material is carried in the lower layers of the ice. It was also a matter of frequent observation that debris lies under the ice. Apparently the ice sometimes pushes this along and sometimes slides over it. At the end of the glacier the debris within the ice is freed by melting and accumulates as a talus-slope. This sometimes protects the basal layers from melting, and they become at length incorporated in the growing accumulation. Their subsequent melting gives rise to one form of kettle-holes, but only one form. It appeared from the stages presented by the several glaciers that where a glacier is slowly advancing the talus-slope gradually grows forward and constitutes an embankment upon which the glacier advances. It thereby grades up its own pathway in advance. On seeing this process one is at no loss to understand how ice can advance over fields of sand or soil without in any way disrupting them. It buries them before it advances upon them. A large number of the glaciers of the Inglefield region rest upon embankments or pedestals of this kind. Some, which have retreated, have left these exposed to observation. (Figure 13, plate 9.)

Where the frontal material accumulates in a large mass it opposes such a degree of resistance to the ice that its layers are curved upward on the inner slope, and if the glacier subsequently advances the ice rides up over the moraine. Several such instances were observed, but none was seen where the ice showed any competency to push even its own debris, in notable quantity, in front of it. The ice is weaker than the moraine as a whole.

WIND-DRIFT BORDER.

Not only is the ice of the north Greenland glaciers weak when tested by the resistance of its own frontal moraine, but it is even weak when compared with the wind-drift accumulations of snow on its front. There is a very notable wind-drift phenomenon connected with the border of the great ice-field of north Greenland to which Lieutenant Peary was the first, I think, to call attention. The winds of the great ice-cap flow chiefly down its slopes, as though by direct control of gravity. They carry great quantities of snow, and this lodges in the lee of the terminal moraine. The border-drift thus formed has a breadth of from 1,000 to

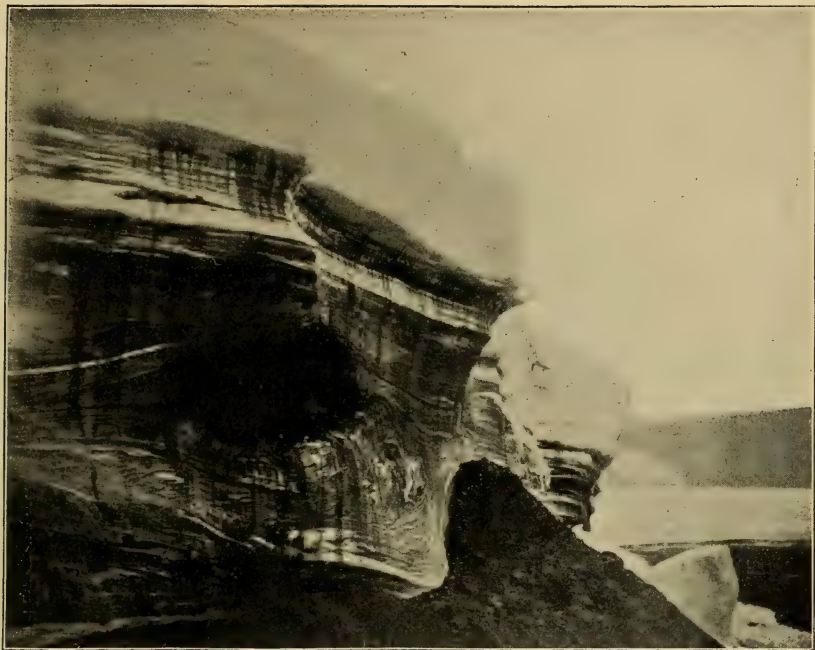


FIGURE 13.—PORTION OF LATERAL FACE OF EAST GLACIER.

Showing the perching of the glacier on its own debris, and the gneiss-like contortion of the laminae, due to the resistance of the mound of debris in front. The overjutting of certain of the upper layers is also shown. Bowdoin bay seen in the distance.



FIGURE 14.—PORTION OF EDGE OF THE ICE-CAP.

Showing upward curving of basal debris-bearing layers, due to the resistance of accumulations in front.

EAST GLACIER AND EDGE OF ICE-CAP.

3,000 feet, and its slope rises from 100 to 250 feet, though a portion of this elevation is doubtless due to a slope of the earth's surface below. This snow remains from year to year and becomes solidified after the fashion of a glacier; indeed, it is little short of a peripheral ribbon-like glacier, skirting the border of the great ice-cap. Between this and the ice-cap, as a narrow line of division, lies the terminal moraine. The three or four sections across this which were open to observation made it apparent that the moraine was formed by the basal layers of the ice-cap curving upward on encountering the resistance of the wind-drift border in front. The upward movement may have been initiated by a concealed moraine below, but superficially, at least, it would appear that even solidified snow in great mass is sufficient to deflect the advancing layers of ice, paradoxical as this certainly seems.

ESKERS AND KAMES.

No eskers or kames were seen in process of formation except in miniature type. Nothing of the kind was seen upon the backs of glaciers, because, with trivial exceptions, there was no material there from which to form them. The basal drainage of the glaciers was found to be chiefly accomplished by streams running along the sides of the glacial lobes. The central tunnels which most alpine glaciers possess were generally absent. The lateral streams frequently tunneled under the glacier or were bridged by snow-drifts, and doubtless when the ice has vanished there will be found terraces and side ridges of gravel analogous to one of the forms of eskers of our drift, but nothing distinct or typical was seen. The radical reason lies, I suppose, in the fact that the total drainage is too small and too narrowly confined to the summer months.

So also, in regard to the kames, it was observed that the drainage from the terminal slope of the ice-cap usually followed the inner side of the terminal moraine for greater or less distances until a low spot was found across which it made its way. These transverse channels doubtless afford an illustration of the manner in which the gravel accumulates on the inner side of a moraine during its growth, and is subject all the time to disturbance by the movement of the ice; but here again only illustrative phenomena were seen.

My observations, therefore, seem to have but one important bearing upon our theories as to kames and eskers. The debris of the great ice-sheet is confined to its lower portion, with trivial exceptions. It is almost absolutely wanting in the upper portion and on the surface. The heights at which it is found in the lower portion are not greater than the heights of kames and eskers; therefore, unless we resort to the violent hypothesis

of supposing that the material was borne from lower to higher altitudes by the streams that formed the kames and eskers, only to be let down again, we are compelled to locate their origin at the bottom of the ice-sheet. This appears to confine hypotheses to the question whether accumulation took place in tunnels under the ice or in channels cut back from its edge.

DRUMLINS.

No drumlins were seen in process of formation, nor were any seen in the abandoned territory, unless we force interpretation in a few doubtful cases. The observations, however, seem to have some important bearings upon the elucidation of drumlins. The limitation of the debris to the basal layers of the ice limits the horizon of drumlin-making, as in the case of eskers and kames. The observations which showed the weakness of the marginal ice in comparison with the resistance of its own debris furnish ground for comprehending the accumulation of masses of drift beneath the edge of the ice.

In describing the behavior of ice in passing over embossments of rock it may be recalled that the laminae were found to start on the frontal side of the embossment and to curve gradually upward and backward and at length downward in the lee, the trend of this curve being quite similar to the profile of a drumlin. I suspect that this is the true drumloidal curve, and that it represents the balance or the accommodation between the force of onthrust on the part of the overriding ice on the one side and the friction and resistance of the ice and debris against the embossment on the other. I suspect that the progressive tendency in such a case is toward the accumulation of debris below this drumloidal line, which was apparently a line of shearing, and that the result of such an accumulation would be a drumlin. Why this particular curve should be assumed is a problem the precise mechanics of which I do not profess to understand, but seeing the curve developed repeatedly I infer that it must be in conformity with the dynamics of ice-motion under these conditions, and that nothing remains requisite to the formation of a drumlin but the lodgment of drift below the drumloidal curve. (Figures 11 and 12, plate 8.)

RATE OF MOVEMENT OF THE ICE.

Lieutenant Peary has commenced a series of observations upon the movements of glaciers of the Inglefield gulf region, both by instruments and by photographs taken at intervals. He found the daily movement of the Bowdoin glacier, the most active in the immediate vicinity of his headquarters, during the month of July to be four-tenths of a foot at the

slowest point, near the east border, and 2.78 feet at the fastest point, near the center, with an average of 1.89 feet for the whole.

The movement of the majority of the glaciers in that region is very much slower; indeed, in most cases it is obviously exceedingly slow. Many of the ordinary signs of movement are absent. In front of the Fan glacier there are cones of granular ice brought down by the surface streams, and also embankments of old snow, soiled, granulated, and half solidified into ice, as though at least a year old, all of which lie banked against the terminal face of the glacier without any indication of movement on its part since their formation. As these lean against the face to heights of 30 or 40 feet at least, it is obvious that there had been no melting of the base of the extremity to counteract the effects of advance. Phenomena of similar import were observed in several other glaciers. The very firm impression was given by such physical signs that the average rate of movement of the glaciers of the region is very slow. At the head of the gulf are a few glaciers which produce large icebergs and which must be notable exceptions to the prevailing slowness of motion.

GLACIAL DRIFT ON ABANDONED TERRITORY.

The amount of drift on the territory once occupied but now free from ice is notable rather for its scantiness than its abundance. On Disco island it was found to be very limited, except along the immediate fronts of the present glaciers. In the Inglefield Gulf region there are at some points very considerable accumulations of drift within a mile or two of the present ice-front, but at the same time much of the territory between the ice-front and the sea bears a very scant covering of drift. No great moraines were seen, nor any thick mantles of drift. The valleys in front of the glaciers are well floored with glacial wash, but even here the rock occasionally appears. Considerable delta-fans project into the gulf, but none of them exceed half a mile in depth.

Consonant with this scantiness of drift, the topography of the borderland shows only moderate evidence of glacial subjugation. It is mildly rounded, but not greatly molded.

ARE THE GLACIERS ADVANCING OR RETREATING?

Several glaciers on Herbert and Northumberland islands showed evidences of retreat; the terrace-like pedestals which they had formerly built were in part abandoned. Three other glaciers showed by the presence of old moraines immediately in front that in the past they had been more extended than at present. These moraines may be a few hundred years old, but they offered no evidence of very great antiquity. One

glacier was seen overriding its terminal moraine in one portion and retreating within it at another. This, taken in connection with the massiveness of the moraine, probably indicates that it has stood practically stationary for a considerable period.

The most remarkable evidence relative to former extension is furnished by a driftless area on the east side of Bowdoin bay immediately adjoining the present great ice-cap. It is obvious that at this point the ice is as far advanced as it has ever been in the recent geologic history of Greenland. The verity of this driftless area is attested not only by the absence of transported material upon it, but by the exceedingly angular, ragged disintegration of the harder terranes of rock embraced in the complex gneissic series and by the deep disintegration of the gneiss itself. The gullies and ravines reveal the fact that the gneiss is deeply decomposed to a soft, rotten mass, which is not only easily crumbled, but is even pliant under the fingers. It was possible to descend steep slopes by thrusting the heels deep into the softened mass. The combined weight of all this evidence puts beyond serious question the verity of the driftlessness of this region. The area is small, not exceeding three or four miles in maximum diameter, and lies between the ice-edge and Bowdoin bay on ground whose average altitude is less than that of the glacier, so that its immunity from glaciation has not been due to elevation. It is clear, therefore, that the ice-border was stayed at this point by agencies concerned in its own development and not by any topographic barrier.

Immediately at the south of this small driftless area there lies in front of the Gable glacier (which is but a short tongue of the main sheet) a stout old moraine, the surface of which has been notably weathered and has become covered with vegetation in the scant fashion of the region. There is nothing in the nature of this moraine to indicate an antiquity beyond perhaps a few hundred years, but its presence at this point seems to indicate that the ice has stood in the vicinity for a considerable period, and therefore that it is probably, on the average, neither much advancing nor much retreating.

FORMER EXTENT OF GLACIATION.

It is evident that the occurrence of even a small driftless area on a border of the widest stretch of the Greenland ice-sheet is extremely significant respecting its former extension. The general scantiness of the drift over the territory immediately outside of the present ice seems also to raise doubt as to any great former extension. There are two other lines of important evidence that bear upon this question. Dalrymple island is a mass of hornblendic gneiss rising from the water's edge to a height of perhaps 100 feet, with steep slopes and ragged surfaces. It is



FIGURE 15.—DALRYMPLE ISLAND, NEAR THE GREENLAND COAST.

Showing unglaciated profile.

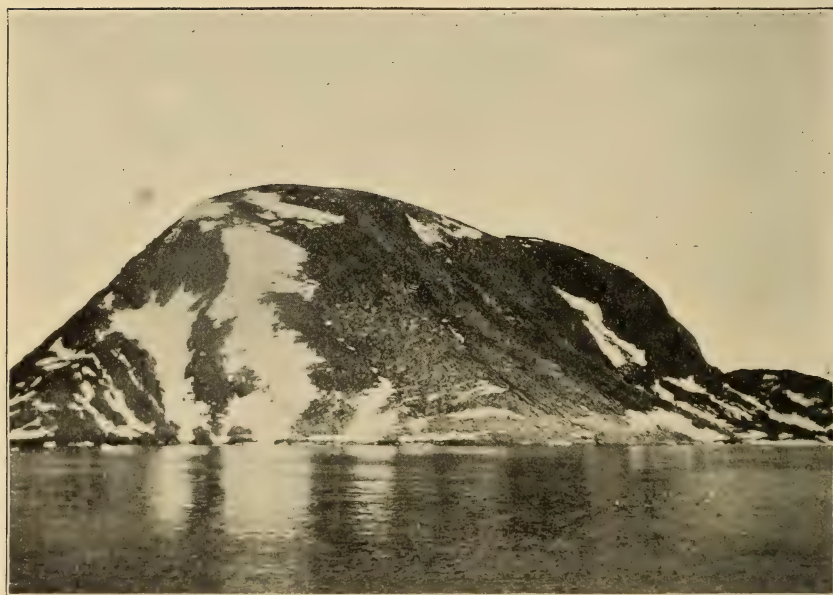


FIGURE 16.—SOUTHEASTERN CAREY ISLAND.

This island is about thirty miles west-northwest of Dalrymple island. The view shows glacial contour produced by movement from the north; not from adjacent coast of Greenland. The geologic structure of Dalrymple and Carey islands is almost identical, the difference in contours being apparently due wholly to glaciation.

DALRYMPLE AND CAREY ISLANDS.

a famous nesting-place of the eider duck, which finds it suitable to its purpose because of this raggedness of surface. The island bears no sign of glacial abrasion. It stands at the mouth of Wolstenholme sound, on the west coast, in about latitude $76^{\circ} 50'$. In other words, it is just off the border of one of the broadest stretches of Greenland's ice-field. Thirty or forty miles distant to the west-northwest lie the Cary islands, which are formed of almost identical rock. They are very notably abraded by glacial action coming from the north. Striae are still preserved upon them at heights of 500 feet above the sea. There also occur upon them erratics of limestone, sandstone, shale and quartzite wholly unlike anything that occurs in the islands themselves. So far as I know, no rock of similar kind occurs in Greenland to the eastward. These erratics appear to have come from the region beyond Smiths sound to the north, either from Grinnell land or from the northwestern coast of Greenland—more likely the former than the latter. It appears, therefore, that while a very notable southerly movement from the far north took place down the valley and reached at least to the Cary islands, there was no corresponding movement from the east. (Figures 15 and 16, plate 10.)

At the very first glimpse of the coastal mountains of southern Greenland I was impressed by their pronounced angularity and the absence, unless it were in the lower valleys, of any notable signs of the horizontal rasping which must have resulted had the inland ice ever pushed across them into Baffins bay. Subsequently I saw approximately a thousand miles of coastline, and an effort was made to discriminate the portions once overridden by ice from those which had not been. Tracts of angular, unsubdued topography were found alternating with tracts of rounded, flowing contours. About one-half of the coast seemed to belong to each type. The inference was drawn that the ice formerly so extended itself as to reach the present coast for about half of its extent, while in the remaining portion the ice fell short.

Combining this topographic evidence with the specific data furnished by a comparison of Dalrymple island with the Cary islands and with the still more stubborn facts offered by the driftless area of Bowdoin bay, the inference seems unavoidable that the ice of Greenland, on its western side, at least, has never advanced very greatly beyond its present border in recent geologic times. This carries with it the dismissal of the hypothesis that the glaciation of our mainland had its source in Greenland.

FORMER ALTITUDE OF GREENLAND.

There is no ground to question the former elevation of Greenland. Its plateaus, like its valleys, indicate this; but glacialists are especially concerned to know whether the former elevation of Greenland was coincident

with its glaciation or not. Aside from the contours of the plateaus and valleys, which seem to indicate a fashioning rather by meteoric agencies than by pronounced glaciation, the driftless area appears to afford the most specific ground for induction. Bearing in mind that this is a small area between the present edge of the ice and sealevel, which would be overridden easily and completely by an advance of the ice-edge of less than five miles, it seems necessary to conclude that at the time of the former greater elevation the climatic agencies of glaciation could not have been what they are now, for the increased elevation would have caused an extension sufficient to overwhelm the little driftless area. If it is safe to conclude that elevation favors glaciation, then it is necessary to conclude that during any period of previous glaciation there was here no elevation sufficient to cause an advance, unless accompanied by counteracting adverse climatic conditions. The raggedness of Dalrymple island bears similar testimony. The general angularity of the coastal mountains of south Greenland throw the weight of their evidence in the same direction. It would appear, therefore, that the former elevation of Greenland was not coincident with conditions favoring glaciation.